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Process Optimisation of Beer Fermentation through Dynamic Simulation

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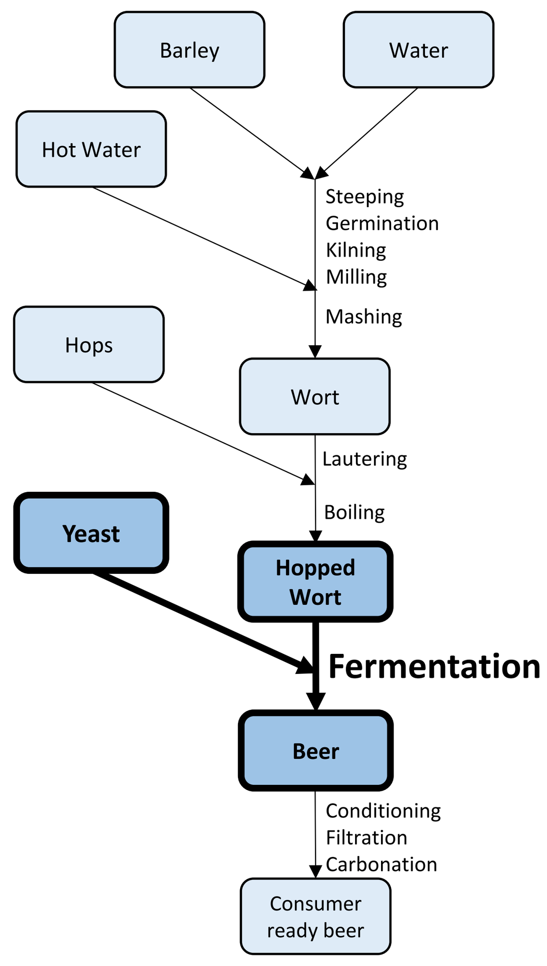
1. Beer Fermentation: Background

Fermentation is an essential step in beer brewing: yeast is added to sugars released from barley grain, which ferment into ethanol (EtOH) and higher alcohols. The process is:

- *Time-consuming* (>120 hours)
- *Energy-intensive* (cooling)
- *Highly complex* (200+ species)

Because this chemical system is sensitive to the imposed temperature profile, fermentation success and efficiency strongly depend on the selection and implementation of *the most effective dynamic temperature manipulation*.

Fermentation tanks (WEST Brewery, Glasgow, UK)



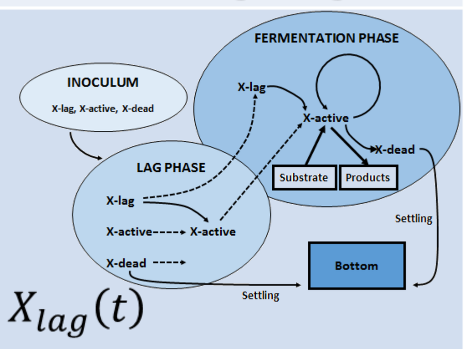
2. Process Optimisation: Project Objectives

This research project has evaluated published kinetic models and then focused on optimal operating conditions, to improve plant performance:

Mashing tanks (WEST Brewery, Glasgow, UK)

- Literature review and evaluation of prior published kinetic models and fermentation optimisation studies.
- Computational implementation of the most reliable kinetic model for fermentation, and assessment of a range of published operating temperature profiles (MATLAB®).
- Computational identification of the optimal temperature manipulation profile via stochastic optimisation.
- Experimental validation vs. WEST industrial production plant data.

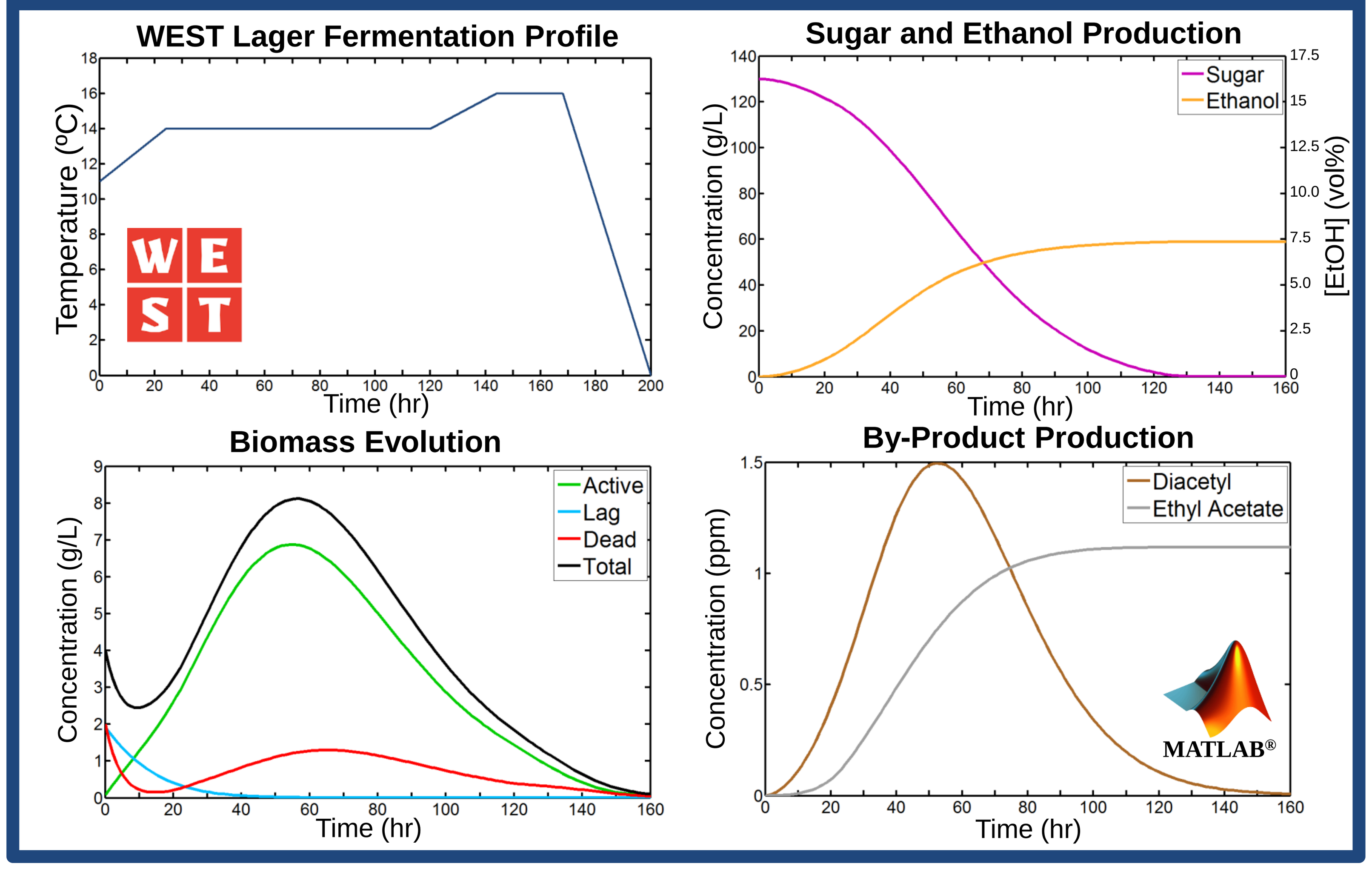
3. Dynamic Mathematical Model of Fermentation

	Beer Fermentation Kinetic Model (B. de Andrés-Toro, 1998)
Alcohol	$\frac{dC_E}{dt} = f \cdot \mu_E \cdot X_{act}(t); \quad f = 1 - \frac{C_E(t)}{0.5 \cdot C_{S0}}, \ \mu_E = \frac{\mu_{E0}(T) \cdot C_S(t)}{K_E(T) + C_S(t)}$
Sugar	$\frac{dC_S}{dt} = -\mu_S \cdot X_{act}(t); \quad \mu_S = \frac{\mu_{S0}(T) \cdot C_S(t)}{K_S + C_S(t)}$
Yeast	$\frac{dX_{lag}}{dt} = -\mu_{lag} \cdot X_{lag}(t)$ $\frac{dX_{dead}}{dt} = -\mu_{SD} \cdot X_{dead}(t) + \mu_{DT} \cdot X_{act}(t)$ $\frac{dX_{act}}{dt} = \mu_x \cdot X_{act}(t) - \mu_{DT} \cdot X_{act}(t) + \mu_L \cdot X_{lag}(t)$ 
By-Products	$\frac{dC_{EA}}{dt} = R_{EA}(T) \cdot \frac{dC_S}{dt}$ $\frac{dC_{DY}}{dt} = \mu_{DY} \cdot C_S(t) \cdot X_{act}(t) - \mu_{AB} \cdot C_{DY}(t) \cdot C_E(t)$

NOMENCLATURE

- μ_i Substrate consumption rate
- R_i Stoichiometric coefficient
- C_i Concentration
- i Species
- f Inhibition factor
- EA Ethyl acetate
- DY Diacetyl compounds
- lag Latent yeast cells
- act Active yeast cells
- dead Dead yeast cells

4. Dynamic Simulation of Industrial Operation



5. Stochastic Optimisation of Fermentor Operation

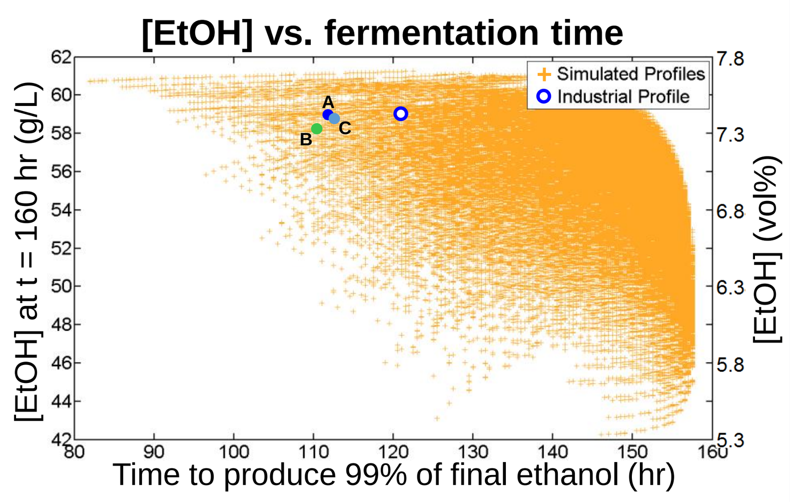
- **Ensemble:** 175,000 unique profiles (MATLAB® run time: 1 hr only!)
- Rapid, comprehensive evaluation of all output profiles for performance

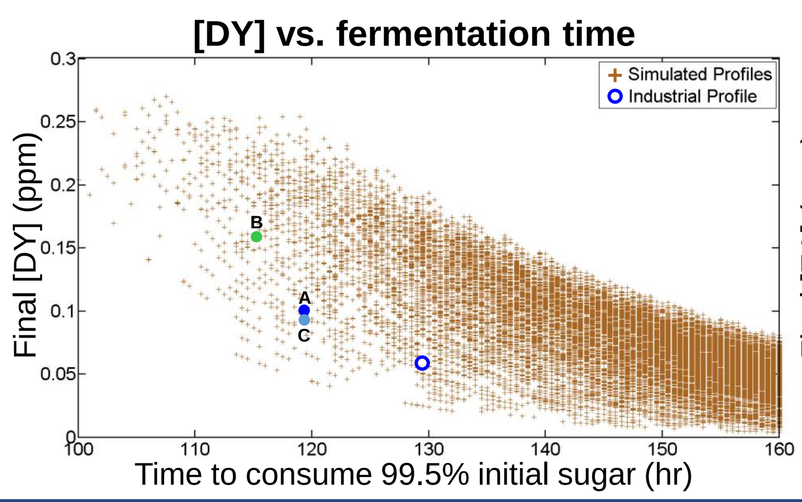
T Profile Generation Constraints:

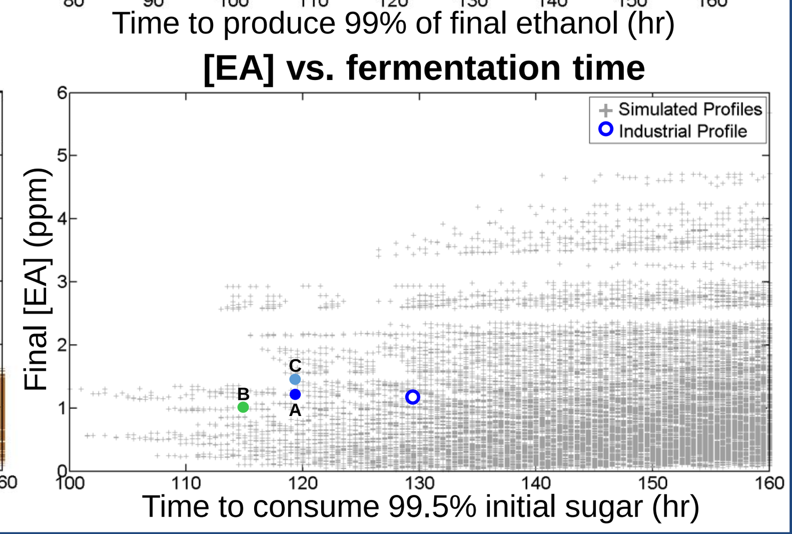
$9\,°C \le T \le 16\,°C$

$T_t \ge T_{t-1}\,; t < 80$ hr

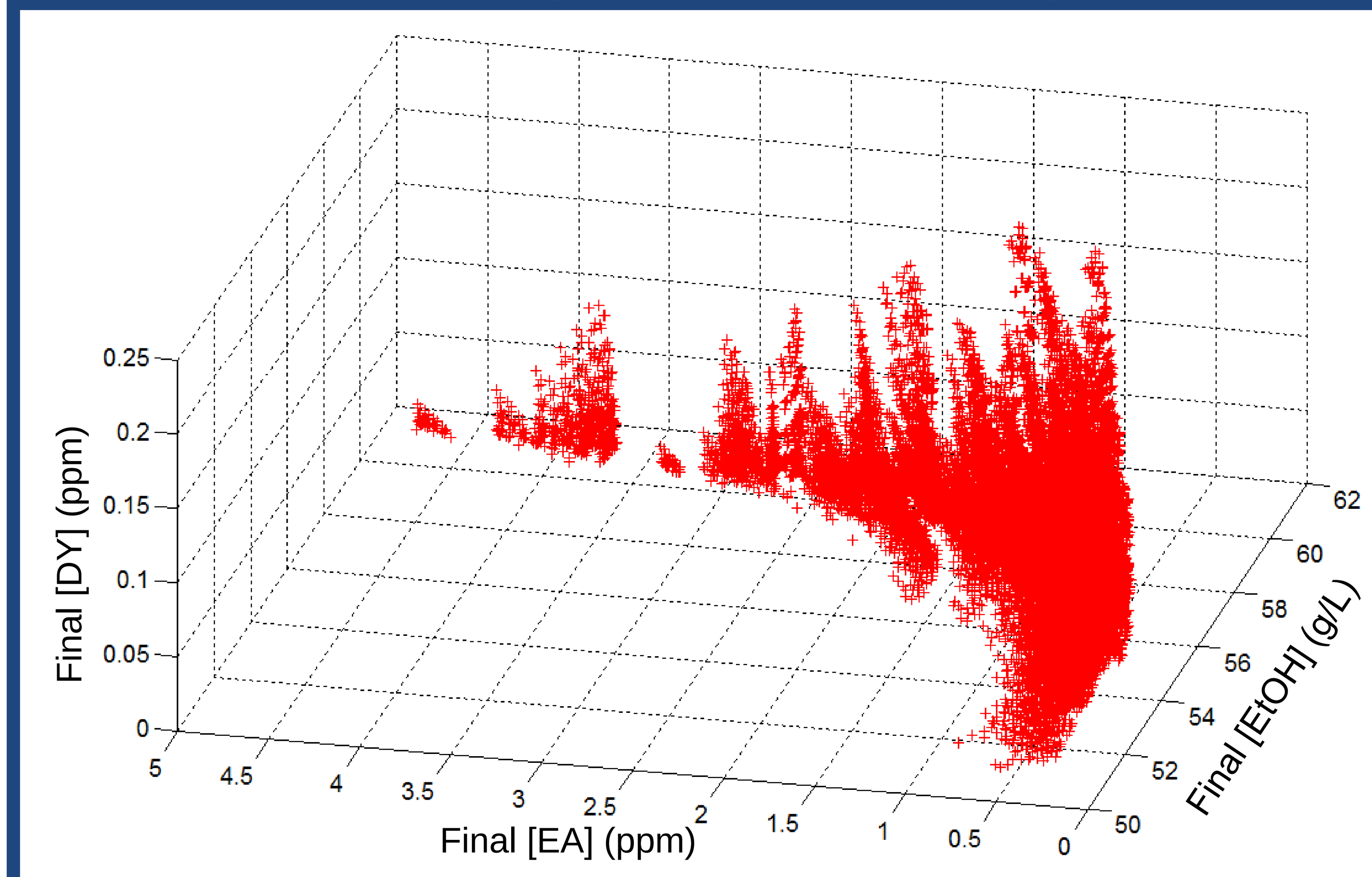
$T_t \le T_{t-1}\,; t \ge 80$ hr



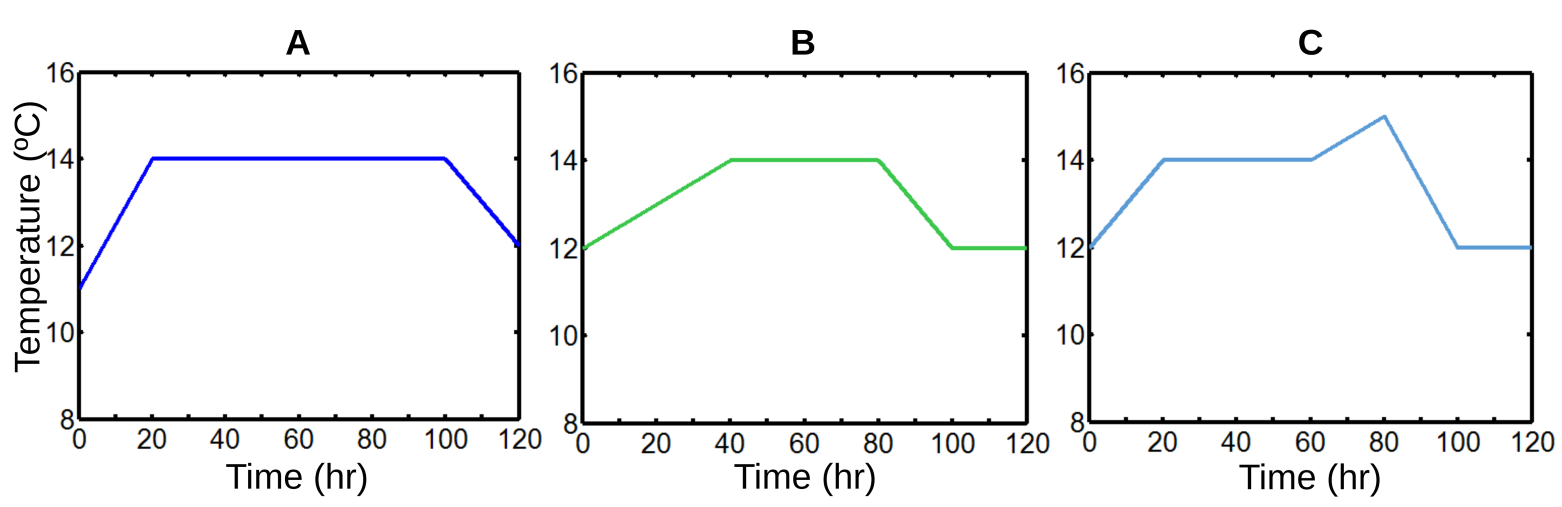




6. Attainable Envelope of Product Compositions



7. Fermentation Process: Operational Improvements



Parameter	Units	Existing WEST Industrial Manipulation	New Operational Improvements A	B	C
Fermentation time	hr	129.5	119.5	115.0	119.5
EtOH concentration	g/L	59.0	58.9	58.0	58.9
EA concentration	ppm	1.16	1.19	0.99	1.28
DY concentration	ppm	0.06	0.10	0.16	0.09

8. Conclusions

- The de Andrés-Toro (1998) model reliably describes beer fermentation
- Performance of published operating profiles is accurately predicted
- Simulation-based optimisation determines key beer quality attributes
- Three new profiles (A, B, C) demonstrate clear process improvements
- Optimal operating temperature profile accelerates beer fermentation
- Fermentation time is minimised without any loss of product quality
- Experimental validation of the model vs. WEST plant data under way

9. Literature References

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